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Mechanical Conditioning to Control Height

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SUMMARY. Mechanical conditioning is an excellent means of regulating the growth of vegetable transplants and some ornamental bedding plants. It improves the stature, appearance, handling characteristics, and overall quality of treated plants. The application procedures reported for transplants have included wind, shaking, brushing, and more recently impedance; all of which result in physical displacement of the growing points. Brushing has been most commonly studied for mechanical conditioning in high density transplant production. Brushing reduces plant height, increases stem and petiole strength, improves insect resistance in the greenhouse, tends to improve stress tolerance and enhance stand establishment in the field, and has no effect on crop yield. Although growers using the technique have been very pleased with the quality of brushed vegetable transplants, widespread commercial application of brushing is limited by a lack of automation.

Mechanical stress inflicted by Wind, rain, hail, animal movements, and many agricultural and horticultural practices, is a powerful force in plant form and development in outdoor or natural settings (Mitchell, 1996). Mechanical conditioning is physical stimulation or stress deliberately applied in order to manage plant growth and quality (Latimer, 1991). Mechanical conditioning reduces plant growth and improves plant strength and stature. It may be applied by rubbing stems, brushing shoots, shaking potted plants or whole flats, vibrating pots or plants, as mechanical impedance, or by perturbing plants with water, forced air or wind. The theory behind the application of mechanical stress for regulation of plant growth and processes in protected environments has been reviewed recently (Latimer, 1991; Latimer and Beverly, 1993; Mitchell, 1996), but much has been accomplished in evaluating methods of application and the application details of interest to transplant producers. In addition, we have made great progress in identifying a wide range of crops responsive to mechanical conditioning (Table 1) and in identifying benefits other than height control.

In transplant production, the goal is to produce plants that will 1) withstand the physical stress of handling, shipping, and transplanting, 2) adapt rapidly to the field environment, 3) become established and resume active growth soon after transplanting, and 4) produce acceptable yields without reduction or delay compared to alternative stand establishment methods. Ideally, the method of growth control should produce a short, stocky transplant with thick, strong stems, and a deep green color, and subsequently improve the posttransplant performance, field establishment and early or total yield.

Since chemical plant growth regulators (PGRs) are no longer labeled for vegetable transplants, growers are limited to cultural or nonchemical methods of growth regulation. Mechanical conditioning can be substituted for PGRs to produce many of the desirable characteristics for a vegetable transplant.

Application methods

The application procedures most studied for transplants have been wind, shaking, brushing, and more recently impedance; all of which result in physical displacement of the growing points. Wind applied with a oscillating or unidirectional fan provided growth reduction of tomato (*Lycopersicon esculentum* Mill.) (Adler and Wilcox, 1987) and underbench aeration (wind) provided a vibration treatment which also effectively reduced the height of tomato transplants grown under high density (Liptay, 1985). Wind obviously causes changes in the microclimate surrounding the plant, and wind stress from fans has been reported to cause desiccation damage to broccoli (*Brassica oleracea* var. *italica* L.) transplants (Latimer, 1990). Although very effective in mechanical conditioning, shaking of individual pots (Mitchell et al., 1975) is not applicable to transplant production However, the automated, mechanical oscillatory shaking (AMOS) device developed to provide a combination shaking and rubbing treatment across an entire greenhouse bench (Beyl and Mitchell, 1977a) may provide a model for transplant treatment.

Brushing transplant shoots has probably received the most attention from researchers working with vegetable transplants and ornamental bedding plants. Brushing provides a tactile or thigmic stimulation of the plant growing points. Generally, brushing reduces plant height, and commonly leaf area and dry weight, but increases stem and petiole strength. Methods of application have included brushing

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plant shoots with a small broom (Takaki et al., 1977), a dusting brush (Hiraki and Ota, 1975), a folded sheet of typing paper (Biddington and Dearman, 1985a), a piece of card board (Latimer, 1990), a suspended aluminum bar (Nakaseko, 1988) or PVC pipe (Sanders, 1994), a steel bar suspended in a cloth sling (Latimer et al., 1991), a wooden dowel rod (Baden and Latimer, 1992; Schnelle et al., 1994), a PVC pipe (Latimer and Thomas, 1991), single or multiple layers of burlap (Autio et al., 1994), and a sheet of polystyrene foam (Garner and Björkman, 1996). The brushing material or mechanism must be sufficiently strong and durable to manipulate the shoots in a high density planting, especially after the treatment has caused the typical increase in stem stiffness and strength and the plants have attained some height. Pöntinen and Voipio (1992) found brushing to be much more effective at reducing transplant height than either wind or shaking.

Mechanical impedance is also a studied method of applying a tactile stimulation to transplants without the abrasion associated with brushing. Using a vinyl net covering as a static counterforce provided growth reduction of chrysanthemum [*Dendranthema grandiflorum* (Ramat.) Kitamura] (Beyl and Mitchell, 1977b) and lily (*Lilium longiflorum* Thunb.) (Hiraki and Ota, 1975). More recently, tomato transplants grown under a sheet of Plexiglas for 15 h per night for 12 consecutive nights were 21% shorter than unimpeded controls and had a 20% increase in stem diameter without affecting leaf dry weight (Samimy, 1993). To address concerns of the length of treatment time, and the expense and impermeability of the Plexiglas, Garner and Björkman (1997) compared rectangular frames covered with fiberglass screening or mylar film to a Plexiglas sheet and used morning (1 h) vs. night (15 h) treatment times. Permeability of the impedance material had no effect on growth regulation and only the overnight treatment gave a commercially useful degree of growth reduction. The authors concluded that impedance is more laborious, requires more equipment, and is less effective than brushing (Garner and Björkman, 1997).

Benefits of mechanical conditioning

EFFECTIVE HEIGHT REGULATION. Mechanical conditioning can reduce plant height by 20% to >50% when compared to untreated plants. These reductions in growth are similar to those attained with chemical plant growth regulators. Adler and Wilcox (1987) reported a 48%, reduction in height of tomato plants treated with either chlormequat chloride or thigmic stress (stem rubbing).

Table 1. Summary of the response of different cultivars of various vegetable transplants to brushing initiated at the cotylendonary stage of development (from Baden and Latimer, 1991).

Crop and cultivar	Stem length (cm) Untreated	Brushed
Tomato		
Sunny	20.4	9.6*
Celebrity	19.0	9.5*
Eggplant		
Black Beauty	14.6	9.2*
Ping Tung Long	9.4	6.2*
Cucumber		
Suyo Long	23.0	16.0*
Sweet Success	26.6	20.5*
Squash		
Dixie	9.6	8.0*
All Seasons	7.0	6.0*
Cream of the Crop	7.3	5.5*
Broccoli		
Early Dawn	8.0	6.9*
Green Duke	7.8	7.3*
Symphony	6.4	6.2
Premium Crop	5.6	5.8
Green Comet	4.9	4.8
Cabbage		
Conquest	5.6	5.0*
A&C #5	4.3	4.0
Rio Verde	4.1	4.1
Gourmet	4.9	4.9
Market Prize	4.3	3.9*

*Significantly different from respective untreated control; $P < 0.05$.

Although tomato has probably been studied more than any other crop with respect to mechanical conditioning, brushing is quite effective on a large number of other vegetable crops including eggplant (*Solanum melongena* L.), cucumber (*Cucumis sativus* L.), squash (*Cucurbita pepo* L.), watermelon [*Citrullus lanatus* (Thunb.) Matsum. and Nakai], and some cultivars of broccoli and cabbage (*Brassica oleracea* var. *capitata* L.) (Table 1) (Latimer and Baden, 1991), Jalapeno and bell peppers (*Capsicum annuum* L.) (B.A. Galloway and J. R. Schultheis, personal communication), as well as lettuce (*Lactuca sativa* L.) and celery (*Apium graveolens* L.) (Biddington and Dearman, 1985a). However, significant cultivar differences also have been identified (Johjima et al., 1992).

In addition, height of several ornamentals, aster [*Callistephus chinensis* (L.) Nees], dusty miller (*Senecio cineraria* DC.), and petunia (*Petunia* x*hybrida* Hort. Vilm.- Andr.), has been effectively reduced with brushing with burlap (Autio et al., 1994). Plant height of columbine (*Aquilegia* x*hybrida* Sims), New Guinea impatiens (*Impatiens* x*hybrida* L.), and marigold (*Tagetes erecta* L.) was reduced 20% to 35% in response to brushing with a wooden pole, but ageratum (*Ageratum Houstonianum* L. Mill.) was not responsive to brushing (Latimer and Oetting, 1997). Plant growth habit appears to affect plant response to mechanical conditioning by brushing, i.e., more brittle or stiff plants receive less bending action than more flexible plants, and thereby exhibit less reduction in plant growth.

PLANT CHARACTERISTICS. In addition to growth control, mechanical conditioning affects other plant characteristics. Specific chlorophyll content is higher in mechanically conditioned tomato (Mitchell et al., 1975), eggplant (Latimer and Mitchell, 1988), lettuce and celery, (Biddington and Dearman, 1985a). In addition, mechanical conditioning increases specific leaf weight of tomato (Heuchert and Mitchell, 1983), eggplant (Latimer et al., 1986), lettuce, celery, and cauliflower (*Brassica oleracea* var. *botrytis* L.) (Biddington and Dearman, 1985a). The darker green, thicker leaves combined with shorter stems enhanced the healthy, vigorous appearance of brushed transplants. Mechanical conditioning also improved plant uniformity in the flat and the subsequent appearance of the plants during handling (Garner and Björkman, 1996; Latimer and Beverly, 1993).

IMPROVED PLANT STRENGTH. Mechanical conditioning also increases stem and petiole strength. Although shaking reduced tomato stem diameter, both ultimate shear strength and the modulus of rupture of stems and petioles were increased in shaken plants (Table 2) (Heuchert et al., 1983). Further analysis of stem structural components indicated an increase in percent cellulose in the fiber component of the shaken tomato stems. Rubbed bean

(*Phaseolus vulgaris* L.) stems were stronger than unrubbed stems (Jaffe et al., 1984), and stem strength increased with increasing duration of treatment up to 14 days. Increased stem strength improves stand establishment in various ways. We have observed clear differences in the toughness of treated plants and recorded less breakage during transplanting. In addition, plants maintained a more upright habit when planted or transferred to outdoor conditions (Latimer and Mitchell, 1988; Samimy, 1993), resulting in fewer stem deformations and less sunscald damage. Increased stem strength may also prove important to plant maintenance during shipping and subsequent handling.

IMPROVED STRESS TOLERANCE? The value of mechanical conditioning in improving tolerance to stress has been less consistent. Although brushing increased drought tolerance of soybean [*Glycine max* (L.) Merrill] (Suge, 1980), brushing slightly decreased the drought tolerance of celery, cauliflower and lettuce (Biddington and Dearman, 1985b). In related work, brushed and untreated cucurbit transplants, subsequently planted in pots of sand, were subjected to cyclic drought stress. Cuticular water loss was higher from detached leaves of the brushed transplants, but transplant growth rate under drought-stressed conditions was the same as that of control plants (Latimer and Beverly, 1994). A recent analysis of water loss from brushed tomato plants (van Iersel, 1997) supports earlier observations that brushed plants use more water than untreated plants (Latimer, 1991). However, due to the reduction in leaf area and other morphological changes, the plants do not appear to suffer greater drought stress under field conditions (Latimer, 1991; van Iersel, 1997). Growers using the procedure estimated a 2-week increase in shelf life of the treated plants (Schnelle et al., 1994).

IMPROVED STAND ESTABLISHMENT. Regardless of the lack of direct effects on stress tolerance, mechanical conditioning can improve field establishment of transplants. One of the best characteristics of brushing as a means of growth reduction is the lack of persistence of the effect after treatment ceases. Plants generally resume normal or accelerated growth within 3 days after treatment is stopped (Mitchell et al., 1975). Liptay (1985) noted that while vibrated tomato plants had 34% less shoot dry weight at the time of transplanting, there was no difference in shoot dry weight after 3 weeks in the field. In two of three broccoli tests, brushed transplants increased in shoot dry weight faster than untreated plants during the first 14 to 21 d after field transplanting (Latimer, 1990). This may be due to the net effect of an accumulation of other growth responses including increased specific leaf weight and specific chlorophyll content, more upright habit with stronger stems and petioles, and less leaf area, which could reduce water loss (Latimer, 1991).

Table 2. Effect of shaking (175 rpm, 20 min twice daily, 12 d) on stem strength of 'Rutgers' tomato seedlings (from Heuchert et al., 1983).

Treatment	Stem Diam (mm)	Ultimate Shear Strength ($g \cdot cm^{-2} x10^{-3}$)	Modulus of Rupture ($g \cdot cm^{-2} x10^{-3}$)
Untreated	5.38	6.92	14.39
Shaken	4.96	8.00	15.90
	**	**	**

**Significant at $P < 0.01$.

Table 3. Effect of brushing treatment on plant growth and thrips damage of greenhouse-grown vegetable transplants (from Latimer and Oetting, 1994).

Crop and Treatment	Stem Length (cm)	Shoot Dry wt (mg)	Thrips: Feeding Scars per plant	Thrips: Leaf area Damaged (%)
Tomato, May 1993				
Untreated	33.1	1110	10.1	10
Brushed	22.1	746	6.7	7
	*	*	*	NS
Watermelon, June 1992				
Untreated	25.1	867	3.0	--
Brushed	17.9	597	1.5	--
	*	*	*	--
Eggplant, May 1993				
Untreated	14.7	519	--	28
Brushed	11.4	479	--	8
	*	*	--	*

NS,*Not significant or significant at $P < 0.05$.

Gartner (1994) evaluated root biomechanics of tomato plants subjected to flexing (to simulate wind). She found that flexed plants had higher root to shoot dry weight ratios and a wider stem at the root-shoot junction, and concluded that flexed plants should be more resistant to forces affecting stems and could potentially withstand more force under windy situations than could an untreated plant. Mechanical conditioning also reduces the incidence of stem pithiness in transplants. In tomato plants subjected to severe drought stress, prior conditioning by brushing reduced the occurrence of pithy or hollow stems from 95% among unbrushed plants to only 5% (Pressman et al., 1983).

IMPROVED INSECT RESISTANCE. In addition to growth responses, brushing of tomato, eggplant, and watermelon transplants generally reduced the number of thrips (*Frankliniella occidentalis* Pergande) (Table 3), and of aphids (*Myzus persicae* Sulzer) on tomatoes, relative to the untreated controls (Latimer and Oetting, 1994). Similar reductions in populations of two-spotted spider mites (*Tetranychus urticae* Koch) were seen in brushed marigold, ageratum and New Guinea impatiens plants (Latimer and Oetting, unpublished data). Brushing for height control may be advantageous in an integrated pest management program in the greenhouse.

LIMITED EFFECTS ON CROP YIELD. Although cultivars vary in their response to mechanical conditioning, little or no effect on yield occurs with plants treated only during the transplant production stage. Brushing greenhouse-grown seedlings did not affect subsequent head weight of lettuce (Wurr et al., 1986) or broccoli (Latimer, 1990), or fruit yield of four cultivars of tomato (Johjima et al., 1992) or of three of four cultivars of cucumber (Latimer et al., 1991). However, pretransplant brushing did delay or reduce fruit production in 'Sunrise' tomato in one experiment (Beverly et al., 1992), and mechanical conditioning during crop production has reduced yield of tomato (Buitelaar, 1989) and potato (*Solanum tuberosum* L.) (Akers and Mitchell, 1985).

Potential commercialization of mechanical conditioning

Currently, large-scale commercial adoption of brushing in transplant production is constrained by both logistical and physiological considerations. Many of the grower concerns of when or how much to treat have been addressed in recent research reports. While some of the current constraints to adoption of mechanical conditioning are researchable problems, some are simply matters of engineering or economics. Brushing by hand is too labor intensive to be economical for commercial application. Some grower initiatives have developed brushing systems for use with the irrigation booms (Sanders, 1994). Additional engineering work in this area could have excellent returns.

MANAGING GROWTH REDUCTION. The degree of growth reduction attained depends on the duration or intensity of the mechanical conditioning treatment. Adler and Wilcox (1987) found that the longer a wind or a rubbing treatment was applied, the more tomato plant height was reduced. In addition, the timing of treatment initiation affected the degree of growth reduction. For example, as the initiation of brushing tomato was delayed from the cotyledonary stage to the third true-leaf-stage (resulting in a range of 8 to 18 days treatment), stem length reductions decreased from 43% to 29% for 'Sunny' and from 37% to 17% for 'Wolfpack' compared to that of untreated plants (Latimer, unpublished data). Similarly, Garner and Björkman (1996) found that growth reduction of tomato depended on the number of days of treatment. When brushing was initiated at a canopy height of 6 cm (first true leaf stage), growth reduction was greater than when treatment was initiated at 8 or 10 cm. As these authors point out, the ability to delay treatment initiation reduces the grower's labor investment in the treatment, increases the flexibility of the treatment, and reduces the potential for disease spread in the treated plants. (See next section on plant damage.) However, brushing must be initiated before the plants become spindly or tall enough to tangle in the flat when treatment is applied.

Recent research in dose response to brushing found that a range of 10 to 40 brushing strokes per day gave similar growth reductions of tomato transplants (Table 4) (Garner and Björkman, 1996) and of pansy plugs (*Viola tricolor* L.) (Garner and Langton, 1997). Furthermore, a time period between the strokes of up to 10 min resulted in the same growth reduction as continuous brushing in both studies. Sanders (1994) cited effective growth reduction of tomato, eggplant and pepper transplants with brushing with eight cycles (back and forth) applied three to six times per day. Although measurements of stem elongation rates found maximum elongation occurred at the end of the light period and the beginning of the dark period, brushing treatments applied in the morning were more effective in reducing tomato transplant height (Garner and Björkman, 1996). Similar morning sensitivity was identified in shaken chrysanthemums (Beyl and Mitchell, 1977b). Thus, mechanical conditioning provides flexibility in growth control, i.e., the treatment can be managed to reduce plant growth as much or as little as desired, within the maximum range of response for the selected species.

MANAGING PLANT DAMAGE. Two cultivars of bell pepper exhibited excessive plant damage for the small amount of growth regulation provided by a brushing treatment (Latimer, 1994). In addition, transplant quality decreased as treatment was initiated at later stages of development. However, peppers grown under subirrigation methods showed no damage to a brushing treatment (B.A. Galloway and J.R. Schultheis, personal communication). Initiation of brushing treatments after leaves have fully expanded results in more damage than for leaves that develop during the treatment period. In all cases, plants should not be subjected to a tactile type of mechanical conditioning when the leaves or growing points are wet as this may increase plant damage as well as the potential for disease spread.

The growth habit or texture of some plants makes them more susceptible to damage than others. Garner et al. (1997) found that although pansies were responsive to mechanical conditioning, impatiens (*Impatiens wallerana* Hook.f.) and geraniums (*Pelargonium* x*hortorum* L.H. Bailey) were too easily damaged by the treatment. Damage of flowers is also a concern, especially for ornamental bedding plants. Although the leaves of New Guinea impatiens were not particularly damaged by brushing, the damage to the flowers was excessive and unsightly (Latimer and Oetting, 1997).

Table 4. Effect of daily treatment dose, number of brushing strokes, on stem length and diameter of 'Ohio 8245' tomato transplants (from Garner and Björkman, 1996).

Strokes/day	Stem Length (cm)	Stem diam (mm)
0	14.2 a[z]	2.34 b
10	11.4 b	2.34 b
20	11.3 b	2.51 a
40	10.6 b	2.52 a
	***	**

[z]Mean separation by Fisher's protected LSD at P=0.05.
,*Significant at P < 0.01 or 0.001.

APPLICATION TECHNOLOGIES. Most of the brushing systems tested to date require that the tops of all brushed plants be uniform to receive similar treatment. This is complicated by growing different species, or cultivars, or plants of different seeding dates, in the same house. This is the primary limitation to commercial use of brushing in transplant production. Sanders (1994) reported successful application of brushing by attaching a bar to the boom irrigation system. Garner and Langton (1997) reported effective growth regulation of pansy plugs with netting attached to the irrigation boom being dragged over the plug trays. A sliding, or rolling, apparatus supporting a brushing bar was also commercially successful on a small scale (Latimer and Thomas, 1991; Schnelle et al., 1994). Growers using mechanical conditioning are very pleased with the treated plants, but agree that the process must be automated to be commercially successful.

Development of alternative methods that reduce physical contact with young plant tissue, such as air blasts

(Beyl and Mitchell, 1977a) or shaking of entire benches, may be more acceptable for a wider variety of crops. These methods also would obviate the need to maintain crops at a uniform height as is required for brushing.

Outlook for implementing mechanical conditioning

Mechanical conditioning is an excellent means of regulating the growth of vegetable transplants and some ornamental bedding plants. It improves the stature, appearance, handling characteristics, and overall quality of treated plants. However, mechanical conditioning must be automated to make it commercially feasible. Growers prefer to apply treatments during non-work hours and desire exact recipes for growth control of individual crops. With the differences in cultivar and species responses, automation on a large scale will be difficult to manage unless the grower is large enough to dedicate entire portions of a greenhouse to one crop and a single planting date. Small scale automation may still be very labor intensive.

New research results which continue to verify the flexibility of mechanical conditioning, especially of brushing, for growth regulation provides more latitude in developing recipes. For plant species or cultivars identified as sensitive to damage from brushing, we must develop conditioning methods that reduce contact. As a cultural practice, brushing interacts with pest management, irrigation requirements and possibly fertilization. Combination of mechanical conditioning with other types of conditioning treatments may improve plant growth regulation and final plant performance. For example, Newport and Carlson (1991) combined drought and negative temperature differential (-DIF) with shaking to attain a 41% height reduction of tomato seedlings grown in flats.

Although mechanical conditioning alone may not attain the ultimate goal of conditioning, to control transplant growth during production and enhance posttransplant productivity, it generally does provide good to excellent growth control with no detrimental effects on transplant establishment or crop productivity.

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